



Environmental accounting of hillslope processes in central Tuscany (Italy)

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Abstract

Many recent research works have been showing so far that in watershed management the concepts of environmental accounting cover a fundamental role. This is even more true when the main purpose is represented by the comprehension of the interactions between natural processes and human activities. In the special case of soil erosion and landsliding, setting up a functional linkage between hazard evaluation and risk assessment is for well known reasons a challenging task.

Aim of this work has been the attempt to devise and apply a general methodology for the assessment of the environmental and economic implications of hillslope dynamics. A watershed located in central Tuscany (Italy) has been chosen to test the application of the method. Here, human settlements and infrastructures have experienced strong difficulties in finding an equilibrium with natural landscape evolution: landslides and soil erosion affect a large portion of the area.

In this context every single development or land use planning has to deal with hillslope dynamics which thus should be accounted for in environmental accounting and impact assessment procedures. This has been accomplished using both distributed semi-empirical hydrological-erosive modelling for computing and estimating soil losses and distributed models for the evaluation of landslide hazard and intensity in terms of factor of safety. The two models have been separately applied and their results suitably added to obtain a multihazard map.

The results of the hazard assessment procedure, coupled with basic environmental accounting data relative to the elements at risk, both on land values and net incomes, show that the methodology yields satisfactory outcomes and could easily be integrated with similar approaches used in environmental accounting.



Introduction

In Central Tuscany, and in particular in the hillsides to the south of Florence, soils with agricultural suitability have a high economic value mainly connected with the production of internationally famous wines and olive oils. For the same reason, though, cultivated parcels exhibit a strong sensitivity even to small disturbances. These can in turn induce potential economic losses which must be considered in farming management practices. Of particular concern in this context are losses derived from sediment production and transport from hillslopes to the footslopes and to the drainage network. Sediment yield and consequently soil losses are produced by two different mechanisms, erosion and landsliding. While the former is a process that acts upon single particles of soil, the latter can be regarded as a general mass movement in which a certain volume of soil is mobilised as a single body. Models that allow to predict the damage caused by these phenomena are very important for the correct production management and optimisation. In particular, there is a diffuse and definite need for easily applicable models, either semi-empirical or physically-based, requiring a small number of well defined parameters and able to yield results which are directly comparable when applied in different areas. Here we propose the application of a three component distributed model aimed at assessing the economic impact of both soil erosion and landsliding on cultivated parcels in the Virginio basin test site (Central Italy).

Test Site

The Virginio river basin is located in Tuscany, about 30 Km south of Florence. It is representative of lithological, climatic, vegetational and land use conditions common to several large agricultural areas in central Italy. Land use is mainly represented by vineyards, olive groves. These activities have long been the principal cause of hillside remodelling. In the flatlands the principal cultivations are wheat, corn and sunflower, the sowing bed of which is prepared generally at the end of the summer. A typical Mediterranean climate prevails with an arid period during summer followed by intense and sometimes prolonged rainfall in autumn, decreasing in winter.

Geological formations outcropping in the area are Pliocene to Pleistocene marine and lacustrine sediments in almost horizontal bedding over which recent fluvial deposits of the Virginio river are deposited. The main terms of this cyclic series are, from top to bottom, *a*: recent alluvial deposits of variable grain size; *Pcg*: cohesive conglomerate deposits with sand to silty matrix; *Pcg-S*: cohesive sands and conglomerates; *Ps*: cohesive sands sometimes alternated with non-cohesive levels; *Ps-ag*: levels of sand and clay materials, sometimes with poor mechanical properties, of very highly variable thickness.

The relief is smoothed and somewhat gentle but in general slope gradients are around 10°, especially where soils are more suitable for the cultivation of vines and olives. This situation strongly conditions the hillslope dynamics as we will see later on.

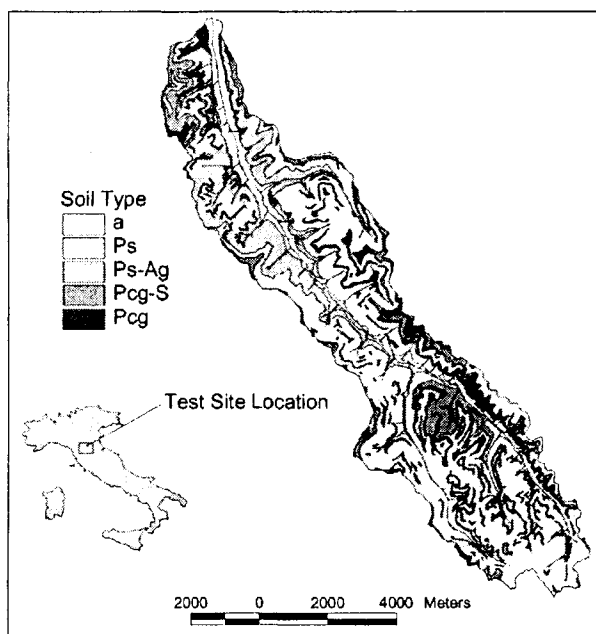


Figure 1 – Test site location and soil map. See text for symbols.

Methodology

In the test site, especially on the hillslopes, processes of sheet and rill erosion, sometimes developing into gully erosion, are strictly linked to the classical parameters conditioning soil losses, such as those included in the universal soil loss equation [1] and its subsequent modifications. In the general form the USLE indicates that soil losses in $\text{ton ha}^{-1} \text{y}^{-1}$ can be computed as:

$$A = R K S L C P \quad (1)$$

This well known expression is especially valid for sheet and rill erosion. When, instead, rills evolve toward a gully trench, the assessment of soil losses becomes a complex matter, which also involves, together with the classical processes, piping, seepage erosion and landsliding.

On the other hand, regular development of sheet and rill erosion on hillslopes is somewhat disturbed by the influence of mass movements of various dimensions and depth apparently randomly scattered. An effective method for assessing potential hazard should hence be based on distributed models at hillslope or sub-watershed scale. In fact, while soil erosion measures can be quite easily extended from profile to profile across the intervening parcels, as long as soil properties remain constant in average, landslide hazard must be calculated in

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two dimensions with the best possible detail. Coupling the two approaches requires the following steps:

- i) selection of the optimal semi-empirical or physically based expression for defining soil erosion or landslide hazard;
- ii) translation of profile-based models to a two-dimensional spatial support;
- iii) application of the coupled model in a GIS environment for the chosen test site.

Soil Erosion Model

As already seen, in the context of risk assessment a rapid decision process is often more important than an accurate evaluation of return time or intensity. This is also true because there is a definite advantage in shortening the time required to put into effect protection or risk mitigation measures, while instead a more detailed modelling procedure does not always guarantee, especially at a basin scale, a better forecast of the expected damage. It is for this reason that we adopted here a distributed version of the well known, easily and widely applicable USLE equation for the assessment of soil erosion.

A spatially distributed approximation of the outcomes of eqn (1) can be computed with small modifications to the classical procedure set up by [1]. Basically, one has to make the assumption that each cell of a rectangular finite elements mesh can be considered as a single USLE soil parcel on which erosion can be separately computed. Since the dimension of a single square cell is 10 by 10 metres, the above hypothesis can be safely considered as valid.

Hence, each parameter can be calculated following the classical schemes with the only exception of the product LS , also known as the "morphological parameter", for the reason that a single cell does not, in most cases, represent the entire hillside nor can it be considered as a complete crop parcel. This affects the computation of LS mainly because along a steepest descent profile two identically constituted cells do show different erosion values due to the different lengths of their respective upslope flow paths. L , and consequently S , are the only parameters which are function of the slope length. In the case of profiles with variable slope many authors (e.g. [2], [3]) suggest to subdivide the entire length in "constant-gradient" sections and to then apply for each of these the standard expression of eqn (2).

$$LS = \left(\frac{L^*}{22.13} \right)^{m^*} (65.41 \cdot \sin^2 \theta^* + 4.56 \cdot \sin \theta + 0.065) \quad (2)$$

where L^* is the total length of the profile in metres and m^* is an empirical parameter that depends on the average profile slope θ^* . The single contribution of the section i is computed by multiplying LS for the relative fraction v :

$$v = \frac{i^{m+1} - (i-1)^{m+1}}{N^{m+1}} \quad (3)$$

where i is the number of the considered section, starting from top ($i=1$) to bottom ($i=N$), and N is the total number of sections. In eqn (3) the value of the exponent m depends on the local slope θ . This procedure can also be adopted for the case of finite elements inside a distributed model simply assuming that:

- the total length L is equal to the square root of the upslope contributing area;
- the average profile slope θ^* can be interpolated using the regression curve of the slope-contributing area diagram for the whole basin, as suggested for example by [4] and [5].

As for the K , R and C parameters, their values, computed via the classical procedures, are summarised in table 1. In order to homogenise the data over the whole basin, the parameter P was not considered (that is $P = 1$) which is to say that our goal is to assess potential economic and geomorphologic damages without considering countermeasures. This choice allows for a more operational approach to be developed, in which the effect and the efficiency of a restoration work would come up instantly and easily. The computation of the USLE erosion values over the finite element mesh has been automatically carried out in a customised GIS environment. Results can be graphically appreciated in Figure 2b where different grey tones represent five classes of erosion potential. As expected, the northern half of the basin shows higher values, especially on the west side where steep slopes are developed on clayey soils. A more detailed description of this partial result will be discussed in the following paragraphs.

Table 1. Experimental values used in models.
R is expressed in $\text{MJ mm h}^{-1} \text{ha}^{-1} \text{y}^{-1}$, K in $\text{ton h MJ}^{-1} \text{mm}^{-1}$

Soil Type	K	c' (KPa)	ϕ' (°)	γ (KN m^{-3})
a	0.0316	5	30	$1.9 \text{ E}10^{-4}$
Ps	0.033	8-10	38	$2.0 \text{ E}10^{-4}$
Ps-Ag	0.0354	5-8	30	$1.9 \text{ E}10^{-4}$
Pcg-S	0.0362	12	45	$2.1 \text{ E}10^{-4}$
Pcg	0.034	12	45	$2.1 \text{ E}10^{-4}$
Land Use		C (USLE)		
Forest		0.007		
Rangeland		0.12	$R = 1104.8$ $P = 1$	
Olive grove		0.36		
Grassland		0.012		
Cultivated crops		0.32		
Vineyards		0.41		

Landslide Model

In the Virginio basin there are principally two dominant types of mass movements, roto-traslational landslides and rock falls. These last will not be considered here, for the following reasons:

- the area affected is very small;
- rock falls in the test site exhibit both an extremely scattered distribution and a very low intensity.

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On the other hand, rotational failures are quite common in the area and, despite their slow rate of movement, show higher intensities because of the greater volumes often involved. For this reason mapping of the factor of safety F has been here elaborated using a distributed version of the expression proposed by [6]:

$$F = \frac{\left(\frac{c'}{\gamma z} \right) + (1 - r_u) \cos^2 \theta \tan \phi'}{\sin \theta \cos \theta} \quad (4)$$

where c' is the peak cohesion in KPa, γ is the bulk density of soil in KNm^{-3} , z is the soil thickness in m, θ is the local slope angle in radians, ϕ' is the peak friction angle in radians and r_u is a ratio expressing pore water pressure. Following [7] $r_u = \gamma_w h_w / \gamma z$, in which γ_w is water density and h_w is the thickness of saturated soil. It is interesting to note that the quantity h_w/z varies between zero and 1 and expresses the fraction of soil thickness which is saturated. The direct determination of saturation indexes is truly difficult but many authors have shown that, under suitable conditions, topographic parameters combined with general transmissivity and rainfall data can be satisfactorily used as proxy variables for h_w/z . In particular, O'Loughlin [8] and Montgomery and Dietrich [9] propose that saturation occurs whenever the following condition is met:

$$\Lambda = \frac{A}{T/q \tan \theta} \geq 0 \quad (5)$$

where A is the specific upslope contributing area, T is the transmissivity and q is the net rainfall rate. Geological and geomorphological conditions in the Virginio basin are such that this assumption can be deemed valid and therefore used to calculate the ratio h_w/z . The empirical relation between Λ and h_w/z can be expressed in the general form

$$\frac{h_w}{z} = a \Lambda^b + c \quad (7)$$

where a , b and c are suitably defined empirical constants.

Averaged values of cohesion, friction angle and bulk density were already available for each soil type as summarised in table 1 [10]. Values of slope angles have been directly computed from the DEM following the steepest descent method. Soil thickness has been interpolated from experimental data adopting the widely used hypothesis that z depends on local gradient and curvature. In fact, among others [11] suggest that:

$$z = -d\theta + f(-\nabla^2 \xi \cdot g) \quad (8)$$

in which $\nabla^2 \xi$ is the local hillslope curvature and d , f and g are empirical constants. The final computation of the factor of safety F , reclassified in four classes of failure hazard, is graphically represented for the whole basin in Fig. 2a. In this map the prevalence of low values of F where soils with scarce mechanical properties outcrop in areas of high relief is clearly visible.

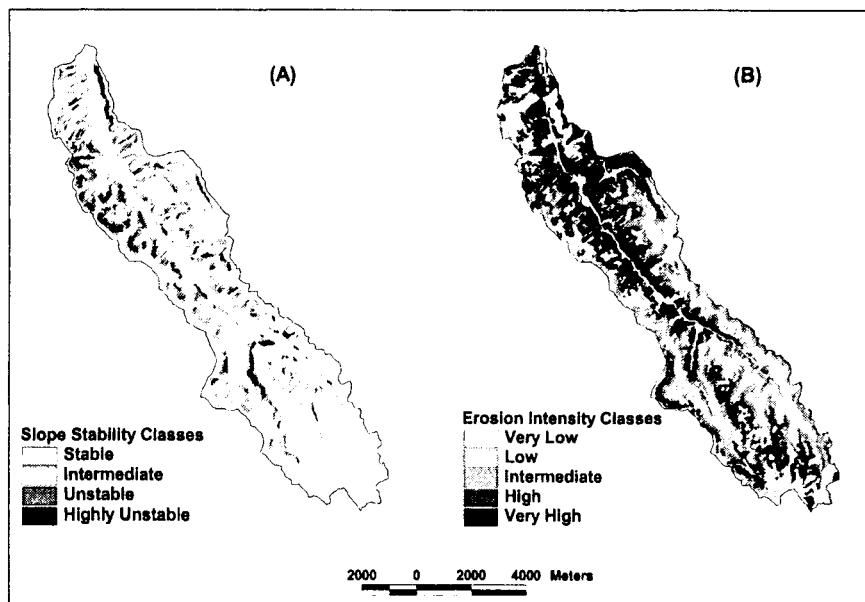


Figure 2 – Slope stability classes (a) and erosion intensity classes (b)

Results and discussion

The overall potential of soil wasting over the basin has been produced by coupling the two models and classifying the output values into five hazard classes (Fig. 3). Owing to the partially different spatial distribution of erosion and landsliding, the combined effect produces more widespread soil losses, especially in the middle part of the basin. The economic outcome of the present landscape dynamics can be at least partially estimated by applying a simple accounting model. Starting from a recently updated land use map, it can be said that in the main the most valuable areas are obviously those occupied by the specialised cultivations of vine and olive from which famous wines and especially healthy and tasty olive oils are produced. For these we used an average value of land valid for the test area as well as an average annual net income produced by the principal types of land use (in euro $\text{ha}^{-1}\text{y}^{-1}$) (Amato, personal communication). Even if these data are approximate and do not take into account the spatial variability of agricultural quality and production, they

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can be considered sufficient for a general assessment of the expected economic losses caused by sediment removal processes.

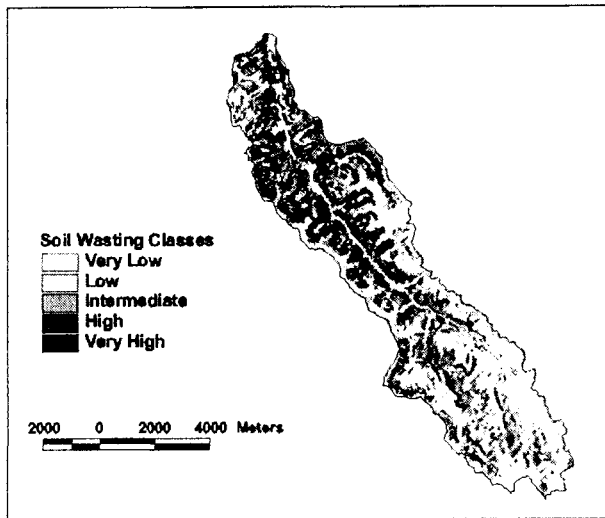


Figure 3 – Soil wasting classes obtained combining the two models

Basically, the potential economic losses after a given period result from the sum of two factors: i) the depreciation of land value and ii) the losses due to the deflection of the averaged annual incomes integrated over time. Afterwards, in order to evaluate the losses actually expected for each land unit, we must connect this data with soil removal hazard distribution. It is known, in this respect, that the decrease of productivity of a cultivated soil is proportional to the quantity of removed material which in turn is linked to time. These relations are represented by S-shaped curves in the graphs of soil production versus time and soil losses versus time, respectively. At small values of time (i.e. t less than a specific time limit t^*) variations are very slow. Then, they suddenly increase as the soil structure becomes more and more disrupted and the process irreversible. The time limit t^* depends on erosion dynamics, soil properties, land use and farming practices. The t^* values for the test site, as well as the exact forms of the empirical relations, have been computed for each different type of soil or cultivation using experimental and literature data (e.g. [3]). In particular, variations in land value over 20 year period have been computed (Fig. 4b), while potential cumulated income reductions have been forecasted over the same period for vineyards, olive groves and other cultivated crops (Fig. 4a).

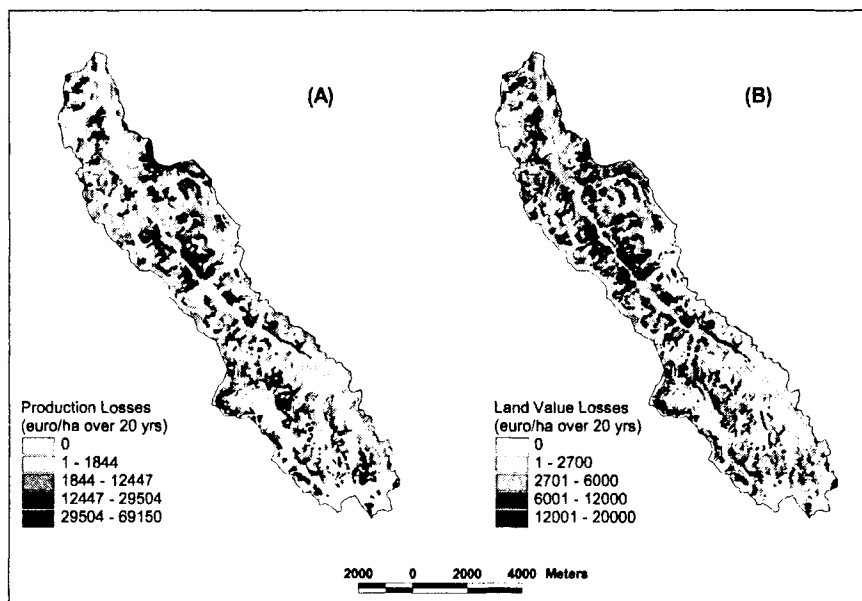


Figure 4 – Production (a) and land values losses (b)

Economic losses range between zero and about 70.000 euro ha⁻¹. Total figures for vineyards sum to about 25 million euro. Table 2 shows cumulative losses in euro for the total area and for the specialised cultivations of greater value. It is important to note that these calculations deliberately do not account for the positive effect of soil protection measures. They merely represent the worst possible scenario under the hypothesised conditions and intend to serve as a measure of the relative importance of geomorphic processes.

Table 2. Partial and total potential losses forecasted by the model. (*) total production losses refer to vineyards, olive groves and cultivated crops only.

	Land value losses in 20 y (€)	Production losses in 20 y (€)
Vineyards	13.814.000	25.502.000
Olive groves	6.121.000	28.094.000
Wheat, corn, sunflower	7.607.000	2.502.000
Whole basin	28.960.000	56.098.000*

Usual conservation practices, such as contour ploughing or terraces are quite expensive to develop on this type of landscape, both for the small average dimension of crops and for the high variability of relief and soil parameters. Some of these countermeasures are nonetheless already used. From the maps in Figure 4 we can easily argue that investments in soil protection are highly useful and necessary. In fact, 49% of the vineyards are potentially affected by high losses. The same is true for 25% of olive groves and 38% of areas cultivated

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with wheat, corn and sunflower. The results globally yielded by the coupled models show that the proposed methodology can prove useful in many cases. First of all, it is easily applicable and very flexible: predictions of increasing precision can be obtained using locally variable parameters instead of averaged quantities but even general estimates demonstrate the robustness of the model. In the context of the study area the most important advantage of the method stands on the possibility of forecasting the potential economic damage to an area of interest in order to plan the optimal protection measures to be carried out. The cost/benefit ratio of each remedial work can in fact be easily evaluated.

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